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THE ELECTRICAL CONDUCTIVITY OF PLANT JUICES.

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(WITH TWO FIGURES)

WITH the recent rapid development of physical chemistry, the physiologist has recognized the fact that the application of the methods of physical chemistry to problems of plant physiology is highly important. Already fruitful results have been obtained in a number of lines, and it only remains for future investigations to increase and supplement them. Since "the conductivity of electrolytic solutions stands in direct relationship with certain phenomena," particularly with the osmotic pressure and with the depression of the freezing-point, it has seemed possible that the determination of the electrical conductivity of plant juices, which are themselves electrolytes, might yield interesting results. Some determinations of this character have been carried out, and although the results are not all that might be expected, they are, to say the least, promising, and will be recorded in the following pages.

The conductivity of electrolytes has been an especially prominent subject in the investigations of physical chemistry, so much so that it may almost be called the *Leitmotiv*. The methods of these investigations and the principles established have recently found application outside the province of physical chemistry. A number of instances may be mentioned. The Division of Soils, U. S. Department of Agriculture, has used the electrical conductivity methods for determining the moisture content[1] of

[1] Bulletin no. 6; also no. 12.

arable soils, and also for determining the temperature[2] and the soluble salt content[3] of soils. Oker-Blom[4] has determined the conductivity of blood, serum, and defibrinated blood for cattle and hogs, but rather from the standpoint of the physical chemist than from that of the physiologist. Recently the rate of flow of underground water[5] has been determined by conductivity experiments.

APPARATUS.

Since the apparatus used is probably not familiar to the majority of botanists it will be described more in detail than

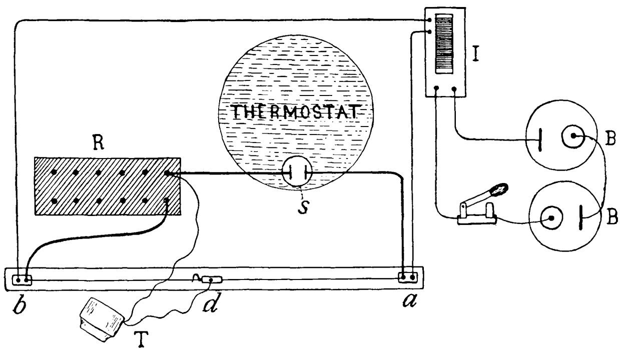

FIG. 1.—For explanation see text.

would otherwise be justifiable. The general plan of the apparatus is represented in *fig. 1*. It consists essentially of a Wheatstone bridge in which the galvanometer is replaced by a telephone (*T*). The resistance is measured along the wire *adb*, which is one meter long, and stretched along a board provided with a millimeter scale. The resistance-box *R* contains resistances of 1, 10, 100, 1000, etc., ohms, and is used for putting into the circuit a resistance nearly equal to that of the electrolytic cell *s*. In order to secure a uniform temperature for all measurements, the electrolytic cell *s* is placed in a thermostat. The windmill thermostat, such as is used in the laboratory of physical chemistry at Leipzig, is the most practical. According to Kohlrausch

[2] Bulletin no. 7.

[3] Bulletin no. 8.

[4] Pflüger's Archives **79**: 111–145.

[5] Science **14**: 972. 1901.

polarization effects can be avoided by using an alternating current of high frequency, and consequently a small induction coil (*I*) of very rapid vibration is added, which serves to transform the current derived from the batteries (*B*).

Since the resistance of solutions varies within wide limits, it was necessary to try a number of different kinds of cells before one was found that was adapted to the work in hand. The first form of cell tried is shown in *fig. 2a.* It has a diameter of 2^{cm}, and the platinum electrodes (*e*) are fused into the ends of glass

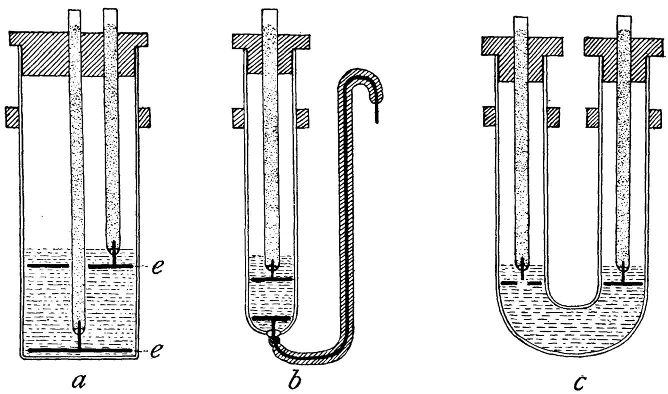

FIG. 2—For explanation see text.

tubes, which are filled with mercury, and securely set in the hard rubber stopper so as to keep the electrodes in a fixed position. The electrodes are covered with a layer of platinum-black by electrolyzing a dilute solution of platinic chloride between them, the object being to increase the surface of the electrodes and thus minimize the polarization effects. This type of cell was found objectionable for two reasons: first, on account of the amount of juice necessary to cover the electrodes; second, because of the small resistance offered, thus making a very indistinct minimum with the telephone. The second form of cell is shown in *fig. 2b.* The diameter of the cell was 8^{mm}, and consequently the resistance of a small amount of solution could be measured, but the minimum obtained with the telephone was indistinct. The form of cell which proved most satisfactory is

shown in *fig. 2c*. In this U-cell the minimum obtained with the telephone was distinct, the amount of resistance inserted in the resistance-box varying from 500 to 2,000 ohms. The diameter of the tube was 6^{mm}, and 5^{cc} of solution was amply sufficient to cover the electrodes.

In order to extract a small amount of juice from the roots, stems, or leaves of plants a special form of press was necessary. This press and the method of obtaining the extract have been previously described.[6]

METHOD.

The capacity of the electrolytic cell must first be determined. This is done by introducing in the cell a solution of known specific conductivity. For this purpose a $\frac{1}{50}$ normal solution of potassium chloride was used, and the thermostat was kept at a temperature of 25° C. This was the temperature at which all subsequent measurements were made, the uniform temperature being necessary, since the conductivity of electrolytes varies with the temperature. After closing the circuit and starting the coil, the movable contact (*fig. 1, d*) is pushed along the graduated resistance *ab* until the minimum for the telephone is found. The resistances are then in the following ratio:

$$R : bd :: s : ad .$$

For the resistance,

$$s = \frac{R \cdot ad}{bd} ;$$

and for the conductivity,

$$\frac{1}{s} = \frac{bd}{R \cdot ad} .$$

The solution used was one of known specific conductivity *l*, so we have the following relation:

$$l = k \times \frac{bd}{ad \cdot R} \quad \text{or} \quad k = l \times \frac{ad \cdot R}{bd} .$$

1 = 0.002765,[7] and from the readings made the value of *k*, or

[6] Jour. Appl. Micr. and Lab. Methods 5 : 1679. March 1902.

[7] LeBlanc, Electrochemie (2te Auflage), p. 77, gives the specific conductivity of $\frac{1}{50}$ normal KCl at 25° C. as 0.002765.

the constant for the cell, can be determined. If now the solution of potassium chloride be replaced by the juice which has an unknown conductivity, and the minimum again found for the telephone, we have the new value from which the specific conductivity can be determined:

$$\text{Specific conductivity} = k \times \frac{bd}{R \cdot ad}.$$

MEASUREMENTS.

With the apparatus and according to the method just described measurements were made to determine the conductivity of the juice obtained from different parts of plants. The following list represents those species used: *Beta vulgaris, Solanum tuberosum, Allium cepa, Raphanus sativus, Nuphar advena, Cucumis sativus, Amarantus retroflexus, Portulaca oleracea.*

1. BETA VULGARIS.

A number of preliminary measurements were made with the juice extracted from the blades of the leaves, the petioles, and the roots, with the following result as an example:

	Specific cond. of juice
Blades of leaves - - - - -	0.03652
Petioles - - - - - -	0.03652
Root - - - - - - - -	0.01891

It will be noted from these results that the specific conductivity for blades of leaves and petioles is the same, hence in the subsequent measurements leaf-blades and petioles are taken together. In order to determine if there was any relation between the conductivity and the amount of ash present in the juice, the crude ash present in 5^{cc} of the juice was found. The crude ash was afterwards dissolved in distilled water, diluted up to the original volume of the juice and the specific conductivity of this solution determined. The result is shown by the following:

	Sp. cond. of juice	Crude ash from 5^{cc}	Sp. cond. of ash sol.
Leaves	0.02676	0.1657^{gms}	0.0296
Root	0.01349	0.0626	0.01105

The conductivity of the juice from the leaves is shown to be double that obtained from the root, and the amount of crude ash is in accord with this fact, although the juice from the leaves has a little more than twice as much crude ash as is found in the juice from the roots. Since perfectly pure water may be considered as practically a non-conductor, it is evident that the conductivity of the juice obtained is due to the substances that were dissolved in the cell sap. From the results obtained for the specific conductivity of the solution containing the ash, it will be seen that the conductivity is due in large measure to the dissolved salts, and that the organic products have played only a slight part if any.

It may be noted here that these facts are in accord with the general statements in regard to the ash content of plants:[8] "that the proportion of ash increases from the root upwards to the leaves." The different varieties of *Beta vulgaris* analyzed by Wolff[9] showed that the leaves contained a much larger amount of crude ash than the roots. It would seem then that the conductivity measurements are here a rough estimate of the relative amounts of ash present in roots and leaves. It must not be forgotten, however, that the juice obtained would not contain all the ash, since some constituents of the ash exist in the plant in the form of insoluble compounds.[10]

2. SOLANUM TUBEROSUM.

Young vigorous plants grown on a heavy black loam were used and measurements made for the juice extracted from the leaves, the aerial stems, and the tubers. The results obtained were as follows:

	Sp. cond. of juice	Crude ash from 5 cc	Sp. cond. of ash sol.
Leaves	0.01959	0.0906	0.01857
Aerial stems	0.02449	0.0781	0.02031
Tuber	0.01505	0.0623	0.01516

[8] VINES, Physiology of plants, p. 130. 1886.

[9] WOLFF, Aschenanalysen, pp. 76–77.

[10] VINES, Physiology of plants, p. 131. 1886.

The specific conductivity for the aerial stems is higher than that for either leaves or tubers, while the amount of crude ash follows the general law already stated that the amount of ash increases from the roots upwards to the leaves. Repeated determinations of the conductivity of the juice taken from different specimens showed similar results, hence it is evident that the conditions here are different from what was found for *Beta vulgaris*. Considering only the tubers and the leaves, the results again show the conductivity to be a rough estimate of the relative amount of ash; but for the aerial stems the conductivity is higher than it should be if ash alone is concerned. How then is the greater conductivity of the juice from the aerial stems to be explained? It is quite probable that it is due in part at least to the greater amount of organic acids present. Titrations of the juice are extremely difficult on account of the color, even when the juice is considerably diluted, but the titrations made indicated more acid than in either leaves or tubers, which are rather alkaline. This conclusion is also substantiated by the specific conductivity of the ash solution, which is considerably less than obtained for the original juice. The relative amount of ash obtained by Wolff[11] for leaves and tubers was slightly different from the above table. His analyses show that the leaves contain nearly three times as much crude ash as the tubers, but a considerable difference was shown by plants taken at different periods in their growth. The different proportions obtained may then be due to the different times and conditions of growth.

3. Allium cepa.

The juice obtained from both leaves and bulbs was measured with the following results:

	Sp. cond. of juice	Crude ash from 5^{cc}	Sp. cond. of ash sol.
Leaves............	0.0125	0.047	0.00921
Bulb..............	0.00525	0.0229	0.00446

[11] Wolff, Aschenanalysen, p. 75.

The specific conductivity of the juice from the leaves is shown to be more than twice that of the juice from the bulb, and the amount of crude ash obtained from 5^{cc} of the juice follows about the same proportion. The figures for the specific conductivity of the solution made up from the crude ash indicate that the ash alone was not the cause of the conductivity of the juice, but that the organic compounds were concerned. Other determinations were made for this species, and all yielded practically the same results. It may also be noticed that the specific conductivity of the juice from the stalk or stem of a specimen in flower is but slightly in excess of that obtained from the bulb. The relative alkalinity of the ash solution of leaves and bulb is as 2.5 : 1, which is in agreement with the specific conductivity of the solution. The determinations of the specific conductivity of the juice are thus shown in this species to be a rough measure of the relative amounts of ash present.

4. Raphanus sativus.

For the common garden radish only specific conductivity determinations were made, using the juice obtained from leaves and root. The results obtained from two different specimens will show how nearly the specific conductivities correspond.

	I. Specific cond. of juice	II. Specific cond. of juice
Leaves............	0.02105	0.02055
Root..............	0.02011	0.01833

The difference here between leaves and roots is less than that obtained for any previous measurements, but the conductivity of the leaf juice is still in excess of that obtained for the root. No ash determinations were made for this species.

5. Nuphar advena.

All of the species used up to this point were taken from places where they had been subjected to about the

same conditions of soil and moisture. It was desirable to make determinations for plants subjected to other conditions, and *Nuphar advena* was selected as a good example of a hydrophyte.

Conductivity measurements and ash determinations were made for the juice obtained from the blades of the leaves, the petioles, the rhizome, and the roots. All parts of the plant used were very carefully washed, and all moisture removed from the surface with filter paper before the juice was extracted. The results obtained are shown in the following table:

	Sp. cond. of juice	Crude ash from 5^{cc}	Sp. cond. ash sol.
Blades of leaves ...	0.009368	0.0328	0.00784
Petioles	0.009368	0.0327	0.00822
Rhizome	0.00761	0.0298	0.00822
Roots.............	0.006113	0.0226	0.00568

The above measurements show that there is a progressive increase in the conductivity of the juice from the roots through the rhizome to the leaves, the measurements for petioles and blades of leaves yielding the same results. The crude ash determinations show a like progressive increase from the roots upwards. The crude ash was redissolved in distilled water and diluted up to the original volume of the juice, and the specific conductivity of the ash solutions determined. The result obtained for the rhizome ash deviates from what might reasonably be expected, being slightly in excess of that obtained for the juice. The others show a slightly lower conductivity than the original juice, showing that part of the conductivity was due to other than ash constituents.

A comparison may be made of the specific conductivities in this species and some of the previous examples. In *Beta vulgaris* the specific conductivity of the juice from the leaves is

three times as great, in *Raphanus sativus* it is over twice as great, and in *Allium cepa* still in excess, although the difference is not great. The results were what might anturally be expected when we consider the aquatic habitat of Nuphar.

6. Cucumis sativus.

For the garden cucumber measurements were made for juice extracted from leaves, stem, and fruit. The roots being small it was not possible to obtain the amount of juice necessary to make the measurements. The results are as follows:

	Sp. cond. of juice	Crude ash from 5^{cc}	Sp. cond. ash sol.
Leaves............	0.0127	0.0621	0.01096
Stem..............	0.0149	0.0609	0.01497
Fruit	0.00632	0.0182	0.00383

This is the only species in which the juice obtained from the fruit was measured, and the examination of fruits of other species is highly desirable. In this instance it will be seen that the specific conductivity found for the fruit is only about half that found for leaves. Here is also another instance in which the specific conductivity of the juice from the stem is greater than that found for the leaves and is not in accord with the amount of crude ash found.

The specific conductivity of the solutions made from the ash of leaves and stem indicates that little besides the ash constituents were responsible for the conductivity of the juice. For the fruit ash, the specific conductivity is but little over half that of the original juice, which indicates that other substances than the ash constituents were concerned. Litmus tests and titrations indicated that the conductivity was produced partly by the acid content of the juice.

7. Portulaca and Amarantus.

Conductivity measurements were made for two more species, and the results will be given together. In each case roots, stems, and leaves were used with the following results ;

	Portulaca oleracea Sp. cond. of juice	Amarantus retroflexus. Sp. cond. of juice.
Leaves............	0.02445	0.01711
Stems.............	0.02154	0.01519
Roots.............	0.01069	0.01328

These figures show that for both species there is a progressive increase in the specific conductivity from the roots upward. No ash determinations were made for either of these species.

The results obtained and recorded in the foregoing pages indicate that a method may be afforded of determining the relative amounts of ash in different parts of the same plant. Conductivity determinations of the juice from the same species grown on different kinds of soil would probably yield interesting results. It is known that the ash of any given species varies in amount throughout the period of growth, and it ought to be possible to determine the extent of the variations by means of conductivity measurements. If this is possible, then the much more laborious process of an ash determination would not be necessary.

It may be noted in this connection that there is a difference of potential between the shoot and root of a plant, the root being electro-negative and the shoot in a state of positive electrification. Whether the greater conductivity of the cell sap in the shoot is in any way connected with this condition remains an open question. The facts at least are suggestive.

CONCLUSIONS.

A number of conclusions can be drawn from the foregoing records of conductivity determinations. Although others are indicated, a greater number of species must be examined before

any more definite relations can be established. From the data at hand the following facts seem established:

1. Plant juices are good conductors, and the conductivity is due in large measure to the dissolved mineral substances, while the organic compounds play a minor part.

2. The specific conductivity of the juice obtained from the roots of plants is always considerably less than that of the juice obtained from subaerial parts.

3. The specific conductivity generally increases progressively from the root upward, although in some cases the sap from the stem has a higher conductivity than that from the leaves.

4. In the majority of cases the specific conductivity is a rough measure of the relative amounts of ash present in different parts of the plant.

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